# Development and Experimental Testing of a Health Monitoring System of Electro-Mechanical Actuators for Small Airplanes

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*Abstract*— **This paper reports the preliminary results of the REPRISE (Reliable Electromechanical actuator for PRImary SurfacE with health monitoring) project, which aims to design a novel Electro-Mechanical Actuator (EMA) to be used on primary flight surfaces of small aircrafts. An important element of the actuator control system is a Health Monitoring (HM) module. This component is an algorithm able to detect anomalies in the device even if there is no evident loss of ability in pursuing its main function (position tracking). In particular, the project aim is to identify any degradation in the mechanical transmission elements, the ballscrew and other components such as bearings. Moreover, it is strongly advisable that the HM algorithm is based on a feature whose value can be easily computed and monitored during the actuator life. In this work, a large experimental activity has been carried out with the purpose of bringing the actuator close to failure, by progressive fault injection in overload operating conditions. A feature named $\Sigma$, that is, the mean of the RMS of the three phase currents (the input to the electric motor), is proposed as a parameter for HM. The effectiveness of this parameter in detecting the mechanical transmission degradation is experimentally tested. The degradation has been confirmed by visual inspection and screw thread profile measurements. In spite of this, the actuator is still able to perform position tracking in an effective way.**

## I. INTRODUCTION

The development of a More Electrical Aircraft is a technological transition conceived over the last decades [1]. This transition may contribute to the apparition of a greener aviation, by reducing the overall aircraft fuel consumption and by removing oil leakage and recycling [2]. Moreover, the employment of Electro-Mechanical Actuators (EMAs) instead of hydraulic systems for primary and secondary surface control will allow very low operating costs, also thanks to a significant weight reduction [3]. Thus, EMAs represent the perfect candidates for flight surface control towards a widespread electric air transportation [4]. There exist examples of early adoption of the so called Power-by-Wire (PBW) technology that preferred the use of electrical systems: Dassault Falcon 7X [5], Airbus A320 [6] and Boeing B777 [7] are just to name some.

However, in spite of the several advantages related to the use of EMA systems, as, for example, considerable reduction of friction between the parts in contact, high efficiency and durability, extended lifespan, excellent dynamic response and noiseless operations, a major drawback of EMAs is the possibility of mechanical failures, in particular of the mechanical transmission, the ballscrew. Due to the high safety standards imposed by the aerospace industry, this leads to the necessity of performing a very expensive periodic scheduled maintenance on such systems.

The latter could be alleviated by the application of Condition Monitoring (CM) or Health Monitoring (HM) systems. The purpose of HM systems is to detect and identify the presence of damaged components, their location and degradation status, even when the system does not show any loss of capability of performing its main function. They aim at recognizing if a component or a device deviates from its healthy/nominal condition even if this is not externally evident, thus preventing potential failures. In this view, HM systems are quite different from traditional standard fault detection systems (see [8],[9],[10],[11],[12],[13],[14]). CM and HM were primarily developed and used in building structures (see [15] for a review) and are widely used in electric motors and electronic components analysis. Some of them are based on the knowledge of an accurate model of the system [16], [17], which is often hard to obtain. More frequently, in electromechanical systems, HM relies on frequency analysis of the vibration of the specimen during operation [18]. This is obtained by using additional sensors, typically accelerometers, to detect anomalies through vibration analysis. (see [17] and [19] as examples). Finally, it is worth noting that the availability of HM systems introduces the possibility of developing lighter maintenance programs, because there is a direct monitoring of the operating conditions of the device. So, instead of a periodically scheduled maintenance, a Condition Based Maintenance (CBM) strategy [20] could be conceived in order to reduce time and costs.

The present work has been developed in the context of the *Reliable Electromechanical actuator for PRImary SurfacE with health monitoring (REPRISE)* - H2020 project (see Section V). The main goal of the project is the development of an Electro-Mechanical Actuator for the control of flight surfaces endowed with a Health Monitoring system, which is the object of this paper. The HM algorithm must be able to prevent critical failures of the component by analysing standard measurements (no additional sensors are used) and to evidence degradation in the EMA behaviour even though no loss of functionality is visible from an external point of view. In the project framework, this paper presents:

- the results of a wide experimental activity with continu-

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ous monitoring of the EMA. To the best of the authors' knowledge, this is the first intensive experimental activity for Health Monitoring on an Electro-Mechanical Actuator specifically designed for aircrafts, employing a 1:1 scale actuator where the aim is to bring it to failure. This is presented in Section II.
- the development of a feature named $\Sigma$, based on the available measurements, whose effectiveness in evidencing the conditions of the mechanical transmission elements has been experimentally proven and confirmed also by visual inspection of the balls and the thread. This has been done even if the EMA did not show any performance degradation in position tracking. This is presented in Section III.

Finally, Section IV is devoted to final comments and recommendations for future directions of research.

## II. Project Overview, Experimental Set-up and Activity

The REPRISE project aims at supporting the improvement of the Technological Readiness Level (TRL) for an electromechanical Flight-Control System (FCS) of small aircrafts, bringing it to TRL 5, developing Health Monitoring algorithms for EMAs in aerospace applications. The final aim of the REPRISE project is to design and realize an EMA endowed with a HM system in order to perform condition assessment on the mechanical parts of the system, especially of the ballscrew.

The EMA used in this paper is a prototype developed for similar applications. It has an Electronic Control Unit (ECU), directly assembled on the actuator, where all the control systems (current, speed and position control) are implemented. The ECU operates through a duplex 28 Vdc power supply for an internal voltage bus that makes the system capable to operate even in case of one supply loss. The position control loop is based on the measurement provided by a Simplex LVDT. The rotational motion is transformed into linear motion by a ballscrew transmission that consists of 8 circuits with 1 turn each. Furthermore, the three phase currents, input to the electric motor, are measured by means of LEM sensors. The system is depicted in Figure 1, where the EMA is in gray color and the ECU is the white upper part.

In order to perform tests on the EMA by applying a load force, the actuator is mounted on the test bench depicted in Figure 2. It is composed by a linear motor for the load application (up to about 2000 N), reproducing the aerodynamic load forces to which the EMA is subjected in real conditions. The applied load is measured by a load cell. A second position sensor is placed on the load side, in order to measure the position also on the load side and to evaluate (possible) non idealities of the ballscrew due to its deformation. The experimental setup is fully described in [21].

In order to pursue the final goal, a large experimental activity has been performed on the EMA. The tests have been conceived to obtain a gradual deterioration of the specimen,

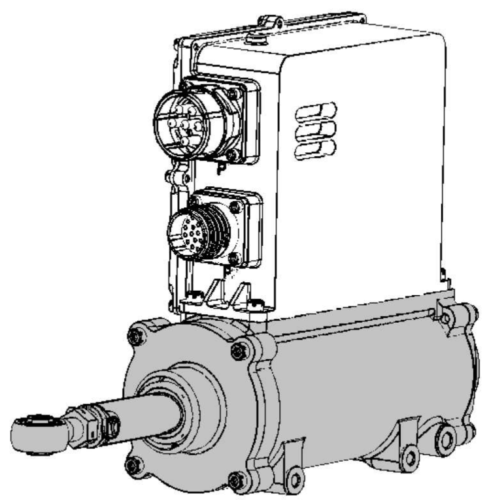

Fig. 1. A graphical representation of the EMA (bottom - grey) and the ECU (top - white)

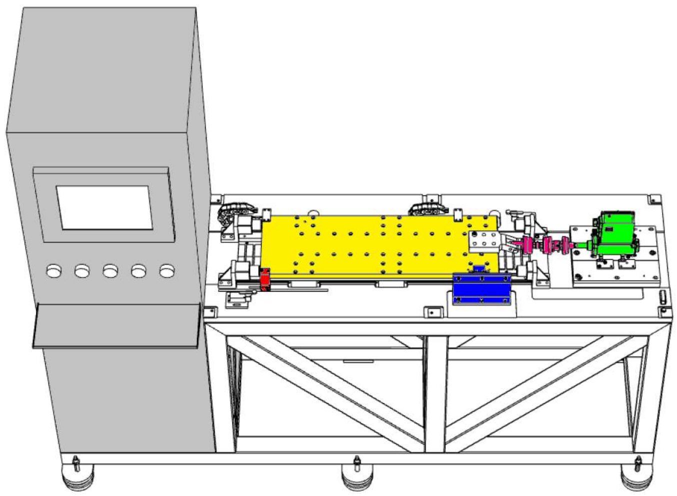

Fig. 2. Test bench schematic representation. The following components are highlighted: linear motor (yellow), EMA (green), load cell (pink), absolute linear optical encoder (blue)

in order to progressively acquire experimental data showing the process of degradation of the EMA until its complete failure. Nonetheless, the employed EMA is constructively extremely robust and intrinsically fault-tolerant thanks to the closed-loop position control systems and current supply redundancy. This means that it could not experience any loss of functionality. Therefore, the position tracking performance will remain within the control system specifications, even though system degradation or component faults have occurred, hiding possible symptoms of incipient faults.

Thus, the tests have been planned taking some actions in order to accelerate the process of deterioration of the mechanical component to be monitored. In particular:

- the EMA has been tested with 3 out of 8 ballscrew ball circuits, in order to increase the pressure at the contact points between the balls and the screw thread;
- the EMA has been connected to the load with an angle

of 17$^o$, so that the applied axial load force will produce a radial component. In this way, a greater contact pressure will be obtained;
- the applied load will be higher than the nominal design load force.

The tests have been executed to simulate the real work cycle of the EMA while it is in flight, which is basically the deflection and the pull-back of the main flight control surfaces. So, the reference position of the position control system is a sinusoidal signal. During the tests, different amplitudes have been used, ranging from 5 mm to 30 mm. Different frequency values were tested, ranging from 0.1 Hz to 10 Hz. The control system has been designed so that the position tracking bandwidth is about 1.5 Hz (see an example in Figure 3).

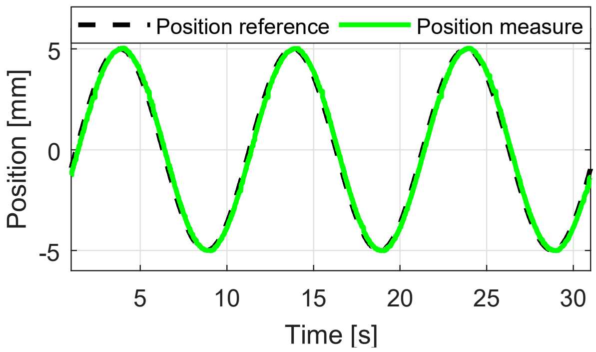


Fig. 3. Example of position tracking at 0.1Hz

Different load force values have been used in the equivalent experiments: initially, a load of 300 N, which is the nominal load condition, has been applied. Then, in order to accelerate the degradation process also higher loads, respectively of 800 N and 1200 N, have been used. These load values have been chosen by means of Finite Element Method (FEM) analysis that predict a 4043 MPa maximum contact pressure between the balls and the screw with 1200 N axial load. This pressure value is about 70% greater than the design maximum value.

Periodically, in order to simulate a "ground-check" of the system functionality, tests with no load are performed. The idea is that the "no load" tests provide information about the operating conditions of the device, i.e. its capability of tracking the assigned position reference.

From April 2017 to July 2017, 1099809 cycles with different amplitude and frequency have been completed:

- 212912 cycles with 300 N load;
- 560730 cycles with 800 N load;
- 212180 cycles with 1200 N load

The remaining 113987 cycles have been performed in other load conditions. During this period, also 4 no-load tests have been performed. In September and October 2017 a specific fault injection has been performed in order to induce a major device stress. In particular, tests have been performed in the following conditions:

- 76640 cycles in various load conditions, with the *lubricant partially removed* from the ballscrew;
- 135600 cycles in various load conditions, where the *lubricant has been completely removed* from the ballscrew.

During this period, also 6 no-load tests have been performed. Globally, the screw has performed 12812958 revolutions (this represents an overestimate since a proper consideration of the EMA dynamic response should be considered).

## III. PRELIMINARY ASSESSMENT OF A HEALTH MONITORING SYSTEM

In order to evaluate the level of degradation of the specimen, the following analysis has been done on the data measured from April 2017 to October 2017:

- *Condition Assessment*: analysis of the three phase currents by means of the calculation of a significant feature. This has been created so that it is possible to evaluate if the "effort" of the actuator is constant over time while performing its main task, i.e. position tracking.
- *Visual Inspection*: the balls and the screw thread are inspected to understand if there is a correspondence between the condition assessment results and the physical status of the mechanical components.
- *Functionality Evaluation*: frequency response models of the position closed-loop behavior of the EMA have been estimated using the "no-load" data. In this way, it is possible to check if the position tracking, which is the main function of the device, is performed correctly over time.

The *Condition Assessment* algorithm is based on the assumption that mechanical components degradation will results in a loss of efficiency of the system. So, in order to obtain a correct position tracking, the EMA will drain more current. So, a statistically robust feature has been conceived and computed according to the following rationale.

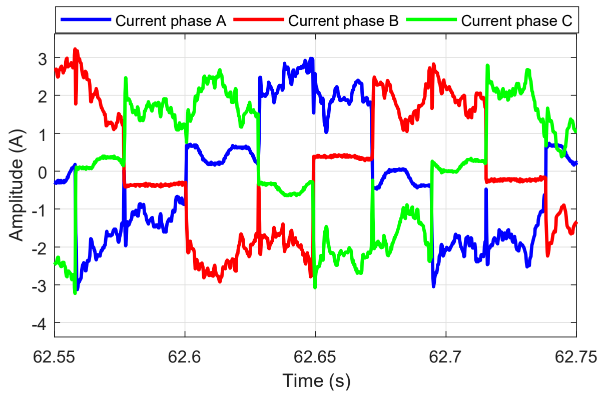


Fig. 4. Example of phase currents measurement

Consider the three phase currents $i_a(t)$, $i_b(t)$, $i_c(t)$ (see Figure 4 as example) measured during an experiment. Since the reference trajectory are sinusoids, the measured position is approximately $x(t) = Asin(\omega t)$, being $A$ the reference amplitude and $\omega$ its frequency in rad/s, so that the period is $T = 2\pi/\omega$. The current signal can be written as:

$$i_k(t), \;\; nT \leq t \leq (n+1)T, \qquad (1)$$

with $k = a, b, c$ and $n = 0, 1, \ldots, N-1$, being $N$ the total number of periods of the considered experiment. For each phase current, we computed the root mean square value over a single period, that is:

$$\sigma_k(n) = \sqrt{\frac{1}{T}\sum_{t=nT}^{(n+1)T} i_k^2(t)}, \;\; k = a, b, c, \;\; n = 0, 1, \ldots, N-1. \qquad (2)$$

Finally, for each experiment, it is possible to compute:

$$\Sigma(n) = \frac{1}{3}\big(\sigma_a(n) + \sigma_b(n) + \sigma_c(n)\big), \qquad (3)$$

with $n = 0, 1, \ldots, N-1$, that can be eventually grouped into a vector $\mathbf{\Sigma}$ with dimension $N$. It is worth noting that is very easy to give a physical meaning to the values $\Sigma(n)$, since they are measured in Ampere. Finally, it is important to notice that the feature $\mathbf{\Sigma}$ is obviously different for each test. In fact, the tests are performed at different amplitudes but also at different frequency values. In particular, $M = 6$ frequency values ranging from $0.1\,$Hz to $1\,$Hz have been used.

The sampling distribution of the elements of $\mathbf{\Sigma}$ is used to represent and explain the results. Specifically, in Figure 5 box plots at different dates and frequency values are represented. There are 6 groups of box plots, one for each frequency ($0.1\,$Hz, $0.3\,$Hz, $0.5\,$Hz, $0.8\,$Hz, $0.9\,$Hz, $1\,$Hz); each group is made of 16 box plots, one for each test date. Each box plot represents the median, the 75th and 25th percentiles, the maximum and minimum values of the available values of $\Sigma(n)$. So, Figure 5 represents the time evolution of the sampling distribution of $\Sigma(n)$ as a function of frequency. From Figure 6 it is clear that changing the operating conditions of the system brings to a change in the statistical distribution of $\mathbf{\Sigma}$. Specifically, in normal operating condition (but for the load excessing the nominal one), the feature median value is slightly decreasing (due to the breaking in of the mechanical components) and its variance is very small. This last characteristic is kept also after that the lubrication is slightly reduced, but with larger median values. The loss of lubrication leads, first, to a rapid increase of the variance of the distribution; second, to a very large increase both in the median value and the variance. Currently, the research work is devoted to the definition of a terse indicator that takes into account this behaviour. The fact that, in Figure 6, the median of the boxplots decreases with time at first instance can be due to the break-in of the actuator. Since $\mathbf{\Sigma}$ can be influenced by load conditions, it follows that a possible test for degradations has to be performed in controlled conditions.

The *Visual Inspection* confirms the results obtained with the calculation of $\mathbf{\Sigma}$. In fact, there is no visible degradation of the balls after use in normal lubrication condition (in April 2017, shown in blue in Figure 6). On the contrary, the balls, after the tests without lubricant (in October 2017, in black in

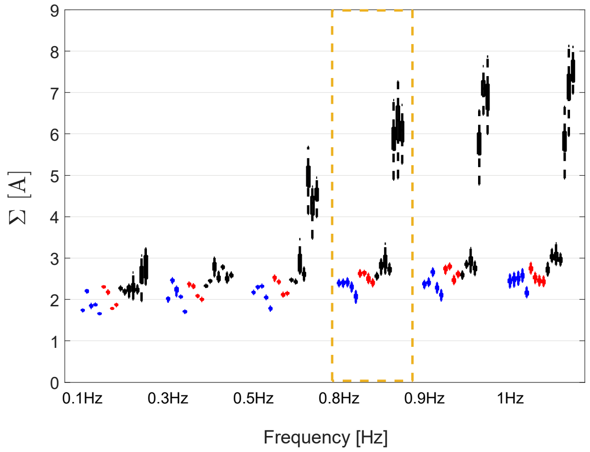


Fig. 5. Sampling distributions of $\mathbf{\Sigma}$ at different dates and frequency values. The evidenced part at $0.8\,$Hz has been depicted in Figure 6

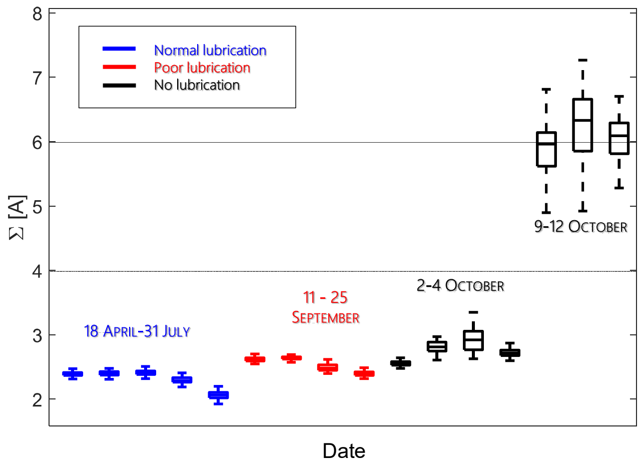


Fig. 6. Time evolution of the sampling distribution of $\mathbf{\Sigma}$ using the data measured at $0.8\,$Hz

Figure 6), are stressed and appear like hammered and opaque (see Figure 7). In fact, due to the high contact pressures and the absence of lubricant, the balls could slide instead of rolling. Furthermore, the radial load induces a different contact angle with which the balls work, and so the balls work nearer the screw's crest. The sliding contact produces a material transfer from the balls to the screw thread and a deformation of the thread itself. In Figure 8 it is possible to see the lucid areas into the thread, due to the balls' passage. Finally, in Figure 9 it is shown the thread profile measured in October 2017 with a profilometer with $0.05\,\mu$m resolution. Notice that the profile is different from the ideal one. In particular, on the left and right side of the thread the balls' pressure has created a channel by plastic deformation, moving the thread material away from the contact point with the ball (on the sides) and pulling it in the center of the profile.

The *Functionality Evaluation* is performed by analyzing the position tracking performance of the actuator. Since

Fig. 7. Balls from one of the circuits after the tests without lubricant. They appear like hammered and opaque.

Fig. 8. The screw thread after the tests without lubricant. It is possible to notice the lucid areas where the balls passed, due to high contact pressures.

the reference signals are sinusoids at different frequencies (and different amplitudes), a frequency response model (one for each amplitude) of the position closed loop has been estimated using the sinusoidal reference position and the measured feedback position ([22], [23]; see [24] for another application of the method). In particular, the model has been built using the no-load data, having in mind that this kind of test could be easily performed during ground maintenance operations. The evaluation has been done by comparing the frequency responses estimated from May to October 2017 with the initial one estimated in April 2017.

In Figure 10 the frequency response estimates at different dates are reported.

The legend reports the dates of the tests (in year 2017).

The comparison has been performed by computing the Relative Squared Error (RSE) $E$ for the frequency response $F(j\omega)$, respectively for the magnitude $|F(j\omega)|$ and the phase $\angle F(j\omega)$. In particular, being $F_A(j\omega)$ the reference frequency response, measured in April, the error index for the magnitude is:

$$E_{mag,i} = \left( \frac{\sum_{\omega=\omega_{min}}^{\omega_{max}} \left( |F_i(j\omega)| - |F_A(j\omega)| \right)^2}{\sum_{\omega=\omega_{min}}^{\omega_{max}} |F_A(j\omega)|^2} \right)^{\frac{1}{2}}, \quad (4)$$

where $i = 1, \ldots, 4$ indicates the date of the tests and $[\omega_{min}, \omega_{max}]$ is the frequency interval covered by the measurements. The corresponding index $E_{pha,i}$ has been

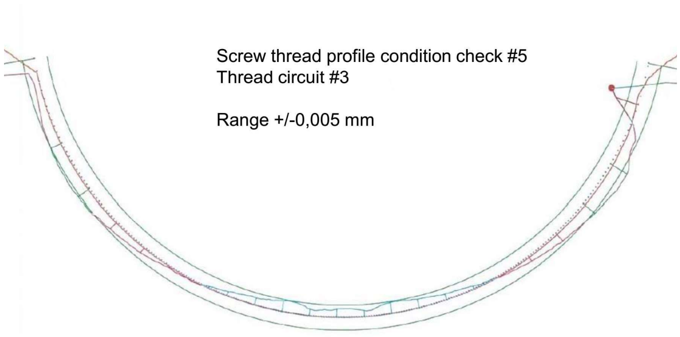


Fig. 9. Profile of the screw thread in one of the areas of higher contact pressure. The thread profile (in light green) is different from the ideal one (in red), it is clearly warped and plastic deformation is evident.

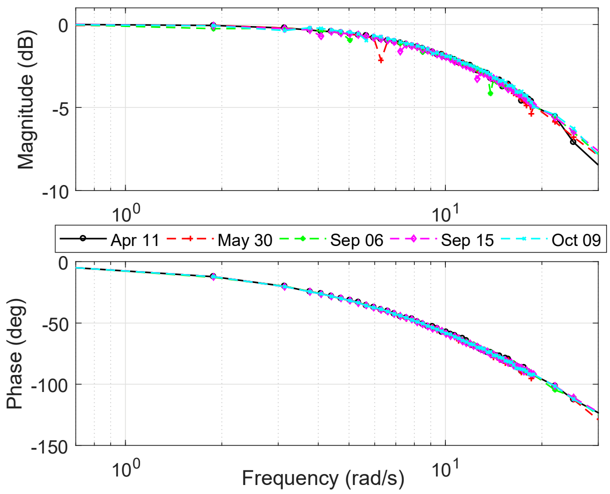


Fig. 10. Frequency responses at different dates

computed with the phase data. These are indexes of how much a test differs from the original one, measured before the beginning of the experimental activity. The results are shown in Table I.

TABLE I

RSE OF THE TESTS WITH RESPECT TO THE FIRST ONE (APRIL 2017)

| $i$ | $E_{mag}$ | $E_{pha}$ |
|---|---|---|
| 1 (May 30) | 0.1564 | 0.0563 |
| 2 (Sep 06) | 0.1082 | 0.0456 |
| 3 (Sep 15) | 0.0975 | 0.0474 |
| 4 (Oct 9) | 0.0953 | 0.0392 |

From Figure 10 and Table I it is clear that the EMA has been able to perform position tracking during all the period of the experiments and, especially, during the October 2017 tests with no lubricant.

## IV. CONCLUSIONS

In this paper, the preliminary results of the REPRISE project have been presented. Specifically, a wide experimental activity has been performed on an EMA designed for flight control surfaces movement in small aircrafts. The goal of this activity is to accelerate the degradation of the mechanical transmission, i.e. the ballscrew. This is obtained by performing a large number of sinusoidal position cycles with external load greater than the nominal one. Moreover, also fault injection has been done, by means of gradual elimination of the lubricant. A physical-based feature has been conceived and computed during the test time. Its value tendency shows that the ballscrew is undergoing strong physical degradation. This is confirmed by visual inspection and mechanical measurements on the ballscrew. Last but not least, the external behaviour of the actuator remained unchanged during the test period, also when mechanical damages were evident. Future research will be focused on the development on an HM method based on the feature $\Sigma$ and to reproduce the same tests on a second EMA in order to validate the effectiveness of the method. Also, following the results of this preliminary work, a complete redesign of the actuator will be performed.

## V. ACKNOWLEDGEMENT

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Clean Sky 2

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